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ANALYSIS OF SHIP MODEL RESISTANCE INTO VISCOUS AND WAVE COMPONENTS

by

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A Station of
Ministry of Technology

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A comprehensive analysis of ship model resistance into viscous and wave components, based on Ship Division, NPL, data, is in hand. This paper first gives a general discussion of the influence of form and scale on model and ship resistance, leading up to the reasons for making the analysis into the viscous and wave components. Then the method used is set out in detail, followed by a discussion of the manner in which the results will be presented and further analyses made to determine the dependence of the resistance on the main hull parameters.

I The Influence of Form and Scale on Model and Ship Resistance

This section is partly a re-statement of the note of the same title presented at the 10th International Towing Tank Conference[1], but there are important modifications and additions.

System for Estimating Ship Resistance

In ship-model work the system used for estimating ship resistance has three main steps:-

(a) the model and ship resistances are correlated at equal values of Froude number

(b) the law of comparison based on dimensional similarity assumes that the "wave" resistance is then proportional to the model or ship displacement;

(c) the "viscous" resistance is "corrected" according to a different law based on Reynolds number.

Current Method of Application

It is usual to discuss model and ship resistance data in terms of a resistance coefficient. A useful coefficient is $\frac{R}{\frac{1}{2}\rho S V^2}$, where R is the resistance, S is the wetted surface area, ρ is the water density, and V is the speed.

The method of applying this system in current practice is:-

(1) the model resistance is measured at various speeds in towing experiments, and values of the total resistance coefficient are obtained;

(2) the "viscous" resistance coefficient of the model is assumed to be the same as the "friction" coefficient of a plane surface having the same length, wetted surface area and speed of advance as the model;

(3) this "friction" coefficient is subtracted from the model total resistance coefficient to give a "residuary" resistance coefficient;

(4) the "viscous" resistance coefficient of the ship is assumed similarly to (2) in relation to the ship dimensions and speed, and is added to the "residuary" resistance coefficient to give the estimated ship total resistance coefficient.

This system and the current method of application are illustrated in Fig. A. Three typical resistance coefficient curves for models of different form are shown. There may be an infinite variety of these, but the same "plane friction" coefficient line is used (or a series of stepped lines in the case of the Froude friction coefficients) for correcting the model results to give the ship estimate. This is done at equal values of Froude number as at O_1 and O_2. While the system has stood the test of time as a practical aid for predicting ship results and is generally accepted as being sound in principle, from Fig. A it is obvious, nevertheless, that the current method of application is open to serious criticism, the chief objection being that the plane friction line or lines used are completely unrelated to the three-dimensional ship forms and take no account of differences in those forms.

New Procedure

The procedure now to be discussed has been developed in the last ten to fifteen years mainly as the result of obtaining much new resistance experiment data, particularly on "plane surface" bodies over a wide range of Reynolds number, and on ship models over a wide range of Froude number including low speeds at which the resistance is almost entirely viscous, the wave resistance being negligibly small.

In the system as outlined above and in the current method of application it is tacitly assumed that the total resistance can be simply divided into the viscous and residuary components and that these two parts can then be considered independently of each other. Before discussing the new procedure it is as well to examine whether this assumption is justified. It is, of course, obvious that there must be some degree of "interaction" between the two parts. A good deal of work, both theoretical and practical, has been done on this subject, but it has not yet been possible to establish a method of allowing for interaction effects in general, nor has it been shown that it is necessary to do so in the resistance scaling problem. On the contrary, recent work[2] has indicated that any such interaction effect as may be present follows, within practical limits, the same scaling law as the main viscous scale effect, at least up to and including the moderate range of Froude number within which most commercial tank testing lies.

The same work[2] also indicated, again within practical limits and for the same range of Froude number, that the fundamental law of comparison may be accepted as correct. It should be added that this demonstration was made in relation to the particular method of analysis which is the basis of the new procedure.

The new procedure is, then, based on these two conditions:-

(1) the law of comparison is correct, and

(2) interaction between the viscous and residuary resistances does not affect the main scaling law.

It follows that the scale effect law must be the same at all values of Froude number and therefore must agree with that at low value of Froude number where the resistance is almost entirely viscous. This principle is, of course, inherent in the law of comparison, but its significance has probably not been fully realised until recently.

The scaling problem as now envisaged is illustrated in Fig. B. This figure shows the correlation of the total resistance coefficient curves of models of different scale, or of model and ship. Turbulent flow is assumed. For the particular hull design the line V_1V_2 is the lowest possible correlation line. It is the line corresponding to zero wave resistance or for which the total resistance is entirely viscous. It corresponds strictly to $F_n = 0$ or $R_n = 0$ and is not physically attainable with a surface model, but it is known that it can be reached experimentally with negligible error at values of F_n below about 0.08 to 0.10, assuming turbulent flow is achieved. At higher values of F_n the line V_1V_2 has no direct physical meaning for the model in question, but it seems probable from a limited amount of experimental evidence that the same line would be obtained from a towing test with the corresponding fully submerged double model, despite the fact that the plane of symmetry would not then be one of constant pressure as with the surface model.

On the basis of the earlier argument it now follows that the line V_1V_2 represents, for all practical purposes, the scaling law for the surface model at all values of F_n. It corresponds to viscous resistance only and may be denoted by the coefficient $C_V = \frac{R_V}{\frac{1}{2}\rho SV^2}$. This coefficient includes all resistance due to viscosity, i.e. the tangential friction resistance and the pressure resistance associated with the formation of the boundary layer. The line V_1V_2 also provides the base from which to measure the "residuary" resistance coefficient. This, for any constant value of F_n, is the intercept T_1V_1 or T_2V_2. In this context the "residuary" resistance may be more appropriately called the "analytic wave" resistance, or simply the "wave" resistance. This is the definition of "wave" resistance as used in this procedure - it is the difference between the measured total resistance and the "viscous" resistance corresponding to the line V_1V_2 at the same value of F_n. The wave resistance coefficient may be denoted by $C_W = \frac{R_W}{\frac{1}{2}\rho SV^2}$, and the total resistance coefficient by $C_T = \frac{R_T}{\frac{1}{2}\rho SV^2}$.

Implementation of New Procedure

The above definition of the scaling law is made entirely without reference to plane friction data. It depends only on the hull form being considered, and it is of course a fundamental principle that this should be so. It is also clear that the scaling law must vary with hull form, being dependent on the value of C_V in relation to Reynolds number.

This dependence can be determined by model experiment. However, the range of Reynolds number for which this can be done is obviously limited, while the possibility of obtaining reliable smooth ship resistance data in sufficient quantity to be of value in this problem is extremely remote. At present the only other means available for determining the scaling law is through a comparison of plane friction and ship model data. Recent

work[2] has shown that this is not only possible but that fortunately there appears to exist a simple relationship between the viscous resistance of ship models and the friction resistance of plane surfaces. This relationship can be expressed thus:- the correlating slope at a given value of Reynolds number depends only on the value of the viscous resistance coefficient, whether this be of a ship model for which the coefficient varies with the characteristics of the hull form, or of a plane rectangular surface for which the coefficient varies with the ratio of length to breadth.

This uniqueness of correlating slope in relation to the value of the viscous resistance coefficient has been established within practical limits for a range of type of hull form and over a considerable range of Reynolds number that is nevertheless limited by model and tank dimensions and does not approach the ship range. However, modern plane friction data extend over a much wider range[3]. Hence, if the above relationship is assumed to apply at all values of Reynolds number, then the means are now available for the implementation of a scaling law or formulation based on these considerations that can be applied with confidence for the prediction of smooth ship resistance from model data.

The above features on which the new procedure is based are illustrated in Fig. C. This shows the pattern of non-intersecting lines of viscous resistance coefficient that was established as the best fit for a large amount of new plane friction data obtained from extensive experiments at the National Physical Laboratory in recent years[3]. The range of these data is marked, and also the more limited range of the ship model data which, within practical limits, gave correlating slopes indistinguishable from those of the plane friction data.

To sum up this section, three conditions for a new formulation would appear to be firmly established as being of paramount importance. These conditions are:-

(a) the scaling formulation will consist of a unique grid of non-intersecting lines, the slopes of which are at all points in agreement with a large amount of data obtained from experiments with both "plane surface" and ship model forms;

(b) the model and ship surfaces must be regarded as three-dimensional forms having their own flow patterns and corresponding values of viscous resistance coefficient, and should not be equated to "equivalent" planks;

(c) the formulation must be applied to the model data in accordance with the values of the viscous resistance coefficient of the model in the low Froude number range where the wave resistance is negligibly small.

It will be observed that in the above there is no reference to a basic formulation for two-dimensional plane surface flow. While from some points of view it may be desirable to define a basic line, this is not an essential requirement in the ship model scaling problem. Equally it is not essential to define levels of viscous resistance coefficient in terms of form factors (though it may be convenient to do so); the <u>value</u> of the coefficient for a given value of Reynolds number is a sufficient definition of "level"

or "position". Therefore the implementation of a method of scale correction for ship models such as outlined above need not be held up because of lack of agreement on the position of the "basic" line or on the precise manner in which "form factor" varies with Reynolds number. It is suggested that in the "levels" in which most ship model viscous resistance data fall there is now adequate evidence to enable a formulation with the above conditions to be agreed and to be applied.

Viscous and Wave Resistance Components

The implementation of the proposed procedure requires the determination in the first instance of the model viscous resistance coefficients. When these are determined it follows that the corresponding wave resistance coefficients are also known. If all available model resistance results are analysed in this way a large volume of data based on a consistent method of analysis will be built up in due course. It should then be possible to co-ordinate these data and to determine the dependence of both the viscous and wave components of resistance on the hull form parameters, so that the results may be easily applied to any scale of model or ship. This is the ultimate purpose of this work. The method to be used for the analysis and the manner of presenting and co-ordinating the results are set out in the next sections.

II Method of Analysis of Ship Model Resistance into Viscous and Wave Components

In the previous section, to explain the basis of the division of the total resistance into the viscous and wave components it was desirable to discuss the resistance coefficients in terms of the model wetted surface S. This was especially so in relation to any comparison with plane surfaces and to the fact that the viscous formulation to be used was derived initially from plane surface friction data.

However, for the practical application to ship models of displacement type the use of S has disadvantages. The ship owner or builder's main interest in the hull form from the point of view of towing efficiency is usually satisfied by knowing the resistance per ton of displacement at a given speed, or in some equivalent form, and this is not readily given if the results are expressed in terms of C_T. The well known Ⓒ and Ⓚ system first introduced by R. E. Froude satisfies this requirement. There are others which also do so, but after much consideration, it was decided that this is the best system to use for this analysis. The chief advantages are (1) the use of Ⓒ is well established and popular; (2) it is the form in which all the model data to be analysed are already expressed; and (3) it was found that the range of value of the model viscous resistance coefficients when expressed in this form is relatively small for a wide range of hull form parameters, thus facilitating the work of co-ordination. The coefficient Ⓚ is less used than Ⓒ, $\frac{V}{\sqrt{L}}$ being more popular, but for this work it is essential to use a properly co-ordinated non-dimensional system and Ⓚ is the obvious choice for the speed coefficient in conjunction with Ⓒ.

The relation between Ⓒ and C_T is $Ⓒ = C_T \times \frac{125Ⓢ}{\pi} = C_T \times 39.8\ Ⓢ$. Conversion from C_T to Ⓒ form does not therefore affect the argument given in Section I so far as application to displacement models and ships

is concerned, but since Ⓢ = ∞ for a plane surface, direct comparison with plane surface friction in terms of Ⓒ has no practical value. However, on the basis of the assumptions made in Section I there will still be a pattern of non-intersecting lines for models and ships in terms of Ⓒ similar to Fig. C, but these lines will have no relevance to plane surface friction. Also the term "form factor", if used as hitherto to denote comparison with the basic two-dimensional line, has no significance in relation to Ⓒ except that its value is always zero. This re-inforces the argument given in Section I that the use of form factors is not an essential requirement in the ship model scaling problem.

Determination of Viscous Resistance Coefficients

The viscous resistance coefficients being defined as in Section I under New Procedure, to determine their values for any model is equivalent to finding the "position" of the line V_1V_2 in Fig. B, or the corresponding line in Ⓒ form denoted by $Ⓒ_V$. There are two ways of finding this position, one wholly experimental and the other a combination of experiment and calculation. In both methods the form of the equation of the line must of course be assumed.

(a) Experimental method

The wholly experimental method is to measure the model resistance at close intervals in the low Froude number[f] range, which experience has shown to be denoted by $F_n \leq 0.08$ approximately. Provided laminar flow is not present to any appreciable extent, the values of the total resistance coefficients in this range may be taken to represent the viscous resistance coefficients for turbulent flow. However, there are considerable difficulties with this method. Because of the low speed very careful experimenting is necessary if the desired accuracy is to be obtained, and particular attention must be given to the determination of the true speed through the water. The extra time required above that for the normal speed range is a very important factor, and on this account alone it is not usually possible to make such tests with many models. Finally the results may prove unsatisfactory if laminar flow effects are present. For the purpose of analysing a large number of results into viscous and wave components, which is the intention of this work, it is clear therefore that this method of determining the viscous coefficients is not acceptable. However, in Ship Division this method was used in a sufficient number of cases covering a wide range of type of hull form to provide basic information, and this led ultimately to the following combined experiment and calculation method being devised and used for the main analysis.

(b) Combined experiment and calculation method

Using the author's proposed viscous formulation[2,3], the total resistance at low and moderate values of Froude number was split into its viscous and wave components for all of those cases in which there appeared to be no

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[f] Although Ⓚ is being used for the speed base, it is convenient to continue to use the term 'Froude number' when speed is being referred to in general terms.

important departure from turbulent flow conditions. It was found that the wave resistance could be represented with negligible error by R_w = constant × (speed)^n, where n is constant up to moderate values of Froude number. The average value of n was about 6, and it appeared that there would also be negligible error if n was taken to be 6 in all cases. Theoretical work by Wigley[4] also shows that the wave resistance at low Froude number varies as (speed)^6. There appeared therefore to be strong support for making the practical assumption that at low Froude number the wave resistance as defined in this analysis varies as (speed)^6. Moreover, the analysis suggested that, ignoring any slight interference humps and hollows, this sixth power variation might be assumed to apply with practical accuracy to the "mean curve" of wave resistance up to values of Froude number approaching or even including service speeds.

In non-dimensional form this sixth power variation for the wave resistance may be expressed as $\textcircled{C}_w = y\textcircled{K}^4$. The viscous resistance formulation is assumed to be $\textcircled{C}_v = x(\log R_n - 2)^{-2}$. This is equivalent to $C_T = X(\log R_n - 2)^{-2}$ in the form proposed in connection with plane friction work[2,3]. A modified form giving a slightly steeper scale correction was proposed for use with ship models[2], but on further consideration it was felt that all practical requirements would be met by retaining the original somewhat simpler form.

The analysis is therefore based on making these assumptions:-

$$ {}_o\textcircled{C} = {}_o\textcircled{C}_v + {}_o\textcircled{C}_w \qquad \ldots (1) $$

$$ {}_o\textcircled{C}_v = x(\log R_n - 2)^{-2} \qquad \ldots (2) $$

$$ {}_o\textcircled{C}_w = y\textcircled{K}^4 . \qquad \ldots (3) $$

The zero prefix to ${}_o\textcircled{C}$, ${}_o\textcircled{C}_v$ and ${}_o\textcircled{C}_w$ is introduced to denote correction to zero tank blockage, this correction being applied to the model $\textcircled{C}$ values before proceeding with the analysis. The method of correction used is given fully in a previous paper[5].

Assumptions (1) and (2) are applied at all values of $\textcircled{K}$. Assumption (3) is applied primarily to the low speed range but may be found to fit the mean curve to any value of $\textcircled{K}$, ignoring humps and hollows. This assumption is initially used solely for the purpose of determining the value of x. When x is found assumption (3) may be of only limited further value, and the actual wave resistance is taken for the subsequent analysis as given by ${}_o\textcircled{C}_w = {}_o\textcircled{C} - {}_o\textcircled{C}_v$.

The analysis is applied as follows. The model $\textcircled{C}$ curve is first corrected to ${}_o\textcircled{C}$. For any such ${}_o\textcircled{C}$ curve or part thereof which conforms to the assumptions (1), (2) and (3) above, there is only one solution, i.e. one value of x and one value of y. In some circumstances these values may be determined by direct calculation, as for example by the method given in the previous note[1] for those cases in which the range of the ${}_o\textcircled{C}$

curve includes the "minimum" point. However, it has been found that, because of the variety of type of $_{o}\textcircled{C}$ curve and of the range covered, there is in general no real advantage in time or accuracy to be gained by any direct calculation method compared with a relatively simple trial process while the latter has one positive advantage. This is that it enables the degree of conformity of the $_{o}\textcircled{C}$ curve with the analysis assumptions to be seen immediately and assists the exercise of judgment in those cases where the value of x is not well-defined. It was therefore decided to adopt the trial method.

Appendix I gives full details of the method adopted for the analysis of the model resistance into the viscous and wave components, and for the recording of the relevant hull form data.

III Presentation of Results for Use and for Further Analysis

For each model analysis a small docket will be prepared, giving:-

(1) A table, similar to the analysis table of Appendix I, but containing only the non-dimensional hull form parameters, the final x and y values, and the $_{o}\textcircled{C}_{w}$ values corresponding to the x value.

(2) A plotting of the $_{o}\textcircled{C}_{w}$ values to base $\textcircled{K}$.

(3) A drawing of the end shapes of the load and half-draught water lines, scaled to a constant half-breadth for easy comparison.

(4) Typical body sections.

(5) Bow profile.

(6) Stern profile.

Each docket will be given the main TM 100 number to identify it with this analysis, followed by an index number thus TM 100/-. The cover will also be marked with three main hull parameter values:- δ_{WL}, $\frac{\nabla^{\frac{1}{3}}}{L_{WL}}$ and its reciprocal $\textcircled{M}$, and $\frac{B}{T}$.

The dockets will probably be grouped in order of δ_{WL} to facilitate further analysis in small ranges of δ_{WL}.

It is proposed to prepare 6 copies only of each docket for record purposes and for use of staff.

References

(1) HUGHES, G. - "The Influence of Form and Scale on Model and Ship Resistance", 10th International Towing Tank Conference, Teddington, September 1963.

(2) HUGHES, G. - "Correlation of Model Resistance and Application to Ship", Trans. R.I.N.A., 1963; also NPL Ship Division Report No. 34.

(3) HUGHES, G. - "Friction and Form Resistance in Turbulent Flow, and a Proposed Formulation for use in Model and Ship Correlation", Trans. I.N.A. 1954.

(4) WIGLEY, W. C. S. - "Calculated and Measured Wave Resistance of a Series of Forms defined algebraically, the prismatic coefficient and angle of entrance being varied independently", Trans. I.N.A. 1942.

(5) HUGHES, G. - "Tank Boundary Effects on Model Resistance", Trans. R.I.N.A. 1961, p.421; also NPL Ship Division Report No. 23 (with R. S. Cutland).

Appendix I

Method for Analysis of Model Resistance Data into Viscous and Wave Components

Procedure

A sample data sheet is shown in Table 1.

1. The analysis is required at regular intervals of Ⓚ, at 0.10 spacing, covering the whole range of the resistance data.

2. The corresponding values of $V/\sqrt{L_{BP}}$ (knots $ft^{-\frac{1}{2}}$) and $10^{-6}R_n$ are calculated from the conversion formulae given on the data sheet. The value of ν used is 1.2260×10^{-5} ft^2 sec^{-1} corresponding to 59°F (15°C) in the 1963 I.T.T.C. tables.

3. For record purposes the values of model Ⓒ at 59°F uncorrected for blockage are entered in the table although these values are not required in the subsequent analysis.

4. The values of ${}_{o}Ⓒ$, i.e. the model Ⓒ values of 59°F after correction to zero blockage, are obtained as follows:-

(a) Mean blockage $m = \frac{V}{L_{BP}A}$

(b) $F_{nh}^{\,2} = 0.0885 \frac{L_{BP}}{h} \times \left(\frac{V}{\sqrt{L_{BP}}}\right)^2$

(c) $\left(\frac{\delta V}{V}\right)_b = \frac{m}{1-m-F_{nh}^{\,2}}$

(d) $\left(\frac{\delta V}{V}\right)_a = k\left(\frac{\delta V}{V}\right)_b$, where k is obtained from Table 2.

(e) From points such as a, b ... on the model Ⓒ curve (Fig. 1) draw short lines parallel to the base of lengths aa', bb' ... corresponding to the values of $(\delta V)_a$ calculated for each point. From a', b' ... drop vertically to a", b" ... where a'a", b'b" ... correspond to the values of $\frac{2(\frac{\delta V}{V})_a}{1+2(\frac{\delta V}{V})_a}$ Ⓒ for each point. Points a", b" ... are on the required ${}_{o}Ⓒ$ curve.

This procedure should be applied at sufficient values of Ⓚ or $\frac{V}{\sqrt{L_{BP}}}$ to enable the ${}_{o}Ⓒ$ curve to be drawn on the Ⓒ sheet. The values of ${}_{o}Ⓒ$

at the appropriate values of Ⓚ or $\frac{V}{\sqrt{L_{BP}}}$ should now be read off and entered on the data sheet.

Note (i) It is not desired to record the various steps in the zero blockage calculation, which should therefore be made separately from the data sheet. To enable the $_{o}Ⓒ$ curve to be sketched in quickly it has been found that this calculation is most easily made at simple spacings of $\frac{V}{\sqrt{L_{BP}}}$ (say every 0.04) rather than at the intervals corresponding to the 0.1 spacing of Ⓚ. Although the correction is usually small it is not unimportant and care is necessary to ensure that it is made accurately in accordance with a uniform procedure.

(ii) At values of F_{nh} above about 0.50 shallow water effects begin to increase rapidly, but our data are not of sufficient coverage to enable corrections for this effect to be made with confidence. Similarly above $\frac{V}{\sqrt{L_{BP}}}$ about 1.2 our data on blockage effects are also insufficient for this purpose. Entries on the data sheet for $_{o}Ⓒ$ should therefore be discontinued when either of these values is reached, but the values for the first four columns $\left(Ⓚ, \frac{V}{\sqrt{L_{BP}}}, 10^{-6}R_n \text{ and } Ⓒ\right)$ should be entered for the whole range of the available data.

5. The viscous component $_{o}Ⓒ_{v}$ is estimated as follows. The calculations are entered on the back of the data sheet.

It is assumed:-

$$_{o}Ⓒ_{v} = x(\log R_n - 2)^{-2} ,$$

$$_{o}Ⓒ_{w} = {}_{o}Ⓒ - {}_{o}Ⓒ_{v} .$$

Trial values of x are assumed and the corresponding values of $_{o}Ⓒ_{v}$ are calculated.* Log $_{o}Ⓒ_{w}$ is then plotted to base log Ⓚ. A typical plotting is shown in Fig. 2. The required value of x is that for which $_{o}Ⓒ_{w}$ agrees with the form $yⓀ^{4}$ in the low speed range. Such agreement is indicated by linearity at slope 4.0†. The value of x is chosen for which this agreement appears to be best. In making this choice consideration must be given to the Ⓚ range of the data, to possible effects of laminar flow at low speed, and to the relatively large percentage effect of small errors at low speed due to the values of $_{o}Ⓒ_{w}$ in this region being very

*Values of $100(\log R_n - 2)^{-2}$ are given in Table 3 from which the values of $_{o}Ⓒ_{v}$ for any value of x are readily obtained.

†When the data sheet was originally prepared it was intended to assume $_{o}Ⓒ_{w} = yⓀ^{p}$ and to find a "best" value of p. Later it was decided to assume $p = 4$ in all cases.

small. Experience has shown that consistent values of x can usually be estimated in this way, provided the Ⓚ range extends to sufficiently low values for the assumed form of the wave resistance to be valid.

For the selected value of x the values of $_{o}Ⓒ_{v}$ and $_{o}Ⓒ_{w}$ are entered on the front of the data sheet. The value of y corresponding to the selected value of x is entered on the back.

6. The hull design parameters required for the subsequent correlation analysis are listed in the left hand column on the front of the data sheet. Since this sheet was prepared it has been found desirable to add δ_{WL} and Ⓜ. These can be inserted as shown.

Nomenclature and Definitions

A	=	tank section area A = 324 ft² No. 1 tank 178 ft² No. 2 " 1200 ft² No. 3 "
h	=	tank depth of water. h = 12.0 ft No. 1 tank 9.16 ft No. 2 " 25.0 ft No. 3 "
L_{WL}	=	model length on water-line, at rest in test condition
L_{BP}	=	model length between perpendiculars
B	=	model breadth
T	=	model draught (mean draught, or draught at midships, if trimmed)
Trim	=	slope of keel at rest, expressed in radians. (This will be assumed to be trim aft unless otherwise specified.)
∇	=	model volume of displacement
S	=	model wetted surface area, at rest
Rise of floor	=	transverse slope of bottom at midships, expressed in radians
β	=	midship section coefficient
δ_{BP}	=	block coefficient, based on L_{BP}
δ_{WL}	=	block coefficients based on L_{WL}
Ⓜ	=	$\frac{L_{WL}}{\sqrt[3]{\nabla}}$
Ⓢ	=	$\frac{S}{\sqrt[2/3]{\nabla}}$
$\bar{x}$	=	distance of centre of buoyancy aft of forward end of water-line

b = distance of bow profile aft of forward end of water-line, at the level line drawn parallel to the water-line at depth 0.5T below it (Fig. 3)

$L_{0.5T}$ = length of level-line at 0.5T below the water-line (Fig. 3)

$\tan \alpha_1 \ldots \tan \alpha_{12}$ are the tangents of the angles defining the water-line and level-line shapes (Fig. 3)

α_m = mean angle giving the same level plane area (Fig. 3)

A_B, A_R, A_M are standard bulbous bow definitions (see separate instructions)

V = model speed in general

R_n = Reynolds number = $\frac{VL_{WL}}{\nu}$

ν = kinematic viscosity of water. Here only the value at 59°F (15°C) is required. This is 1.2260×10^{-5} ft^2 sec^{-1} as given in the 1963 I.T.T.C. tables.

m = mean blockage = $\frac{\nabla}{L_{BP}A}$

F_{nh} = $\frac{V}{\sqrt{gh}}$

k = coefficient used in blockage correction

$\left(\frac{\delta V}{V}\right)_b = \frac{m}{1-m-F_{nh}^2}$ = theoretical blockage speed correction ratio

$\left(\frac{\delta V}{V}\right)_a = k\left(\frac{\delta V}{V}\right)_b$ = actual blockage speed correction ratio

$\textcircled{K} = V \Big/ \sqrt{\frac{g\nabla^{\frac{1}{3}}}{4\pi}}$ = $\frac{\text{speed of model}}{\text{speed of wave of length } \frac{1}{2}\nabla^{\frac{1}{3}}}$

$\textcircled{C}$ = model $\textcircled{C}$ value corrected to 59°F but not corrected for blockage

$\left[\textcircled{C} = \frac{1000\,R}{\Delta(\textcircled{K})^2}\right.$, where R = resistance and Δ = displacement weight in same units$\left.\right]$

$_o\textcircled{C}$ = model $\textcircled{C}$ corrected to zero blockage

$_o\textcircled{C}_v$ = viscous resistance coefficient in $\textcircled{C}$ form. Here this is assumed to be given by

$$_o\textcircled{C}_v = x(\log_{10} R_n - 2)^{-2}$$

$_o\textcircled{C}_w$ = wave resistance coefficient in $\textcircled{C}$ form

$_o\textcircled{C}_w$ = $_o\textcircled{C} - {}_o\textcircled{C}_v$ by definition. These three coefficients each apply to zero blockage.

x = coefficient in formula ${}_{o}\textcircled{C}_{v} = x(\log R_n - 2)^{-2}$

y = coefficient in formula ${}_{o}\textcircled{C}_{w} = y\textcircled{K}^{4}$.

Conversion Formulae

$\frac{V}{\sqrt{L_{BP}}}$ = speed/$\sqrt{\text{length}}$ ratio expressed as knots $ft^{-\frac{1}{2}}$

$$\frac{V}{\sqrt{L_{BP}}} = 0.948 \sqrt{\frac{L_{WL}}{L_{BP}}} \times \sqrt{\frac{\nabla^{\frac{1}{3}}}{L_{WL}}} \times \textcircled{K}$$

$$10^{-6}R_n = 0.1305\, L_{WL}^{\frac{3}{2}} \times \sqrt{\frac{\nabla^{\frac{1}{3}}}{L_{WL}}} \times \textcircled{K}$$

(L_{WL} in ft)

$$F_{nh}^{2} = 0.0885 \frac{L_{BP}}{h} \times \left(\frac{V}{\sqrt{L_{BP}}}\right)^{2} .$$

Important Note This analysis is planned to include all ship types and conditions without discrimination. It is of importance that the greatest care be taken to ensure that the data are entered and the analyses made with the necessary accuracy and that a uniform procedure is maintained throughout. On the last point it is particularly requested that all information be entered in the uniform manner given in the sample sheet, to the same order of accuracy for each item as used in the sample.

TABLE. 1.

SHIP TYPE :- CARGO	MODEL N° —
PROPELLED BY :- SINGLE SCREW	TANK N.P.L. 1
SPECIAL FEATURES :- ——	

A ft^2 324	h ft. 12·0	$m = \frac{\nabla}{L_{BP} A}$ % 0·504	$\frac{L_{BP}}{h}$ 1·54	x 20·6

L_{WL} ft	18·98	SERVICE SPEED $\frac{V}{\sqrt{L_{BP}}}$	BULBOUS BOW TYPES ONLY $\frac{A_B}{A_M}$ %	$\frac{2A_B}{A_M}$ %
L_{BP} ft	18·54			
B ft	2·542			
T ft	0·896			
TRIM	0			

$$\frac{V}{\sqrt{L_{BP}}} \frac{\text{knots}}{ft^{1/2}} = 0.948 \sqrt{\frac{L_{WL}}{L_{BP}}} \times \sqrt{\frac{\nabla^{1/3}}{L_{WL}}} \times (K) = 0.389 \times (K)$$

$$10^{-6} R_n = 0.1305 L_{WL}^{3/2} \times \sqrt{\frac{\nabla^{1/3}}{L_{WL}}} \times (K) = 4.37 \times (K)$$

∇ ft^3	30·27	(K)	$V/\sqrt{L_{BP}}$	$10^{-6} R_n$	(C)	$_oC$	$_oC_V$	$_oC_W$
S ft^2	61·51	1·4	0·544	6·12	0·982	0·962	0·899	0·063
RISE OF FLOOR	0·0108	1·5	0·584	6·56	0·990	0·970	0·888	0·082
β	0·987	1·6	0·622	6·99	1·011	0·990	0·878	0·112
$\delta_{BP}^{\delta_{WL}}$	0·702 0·718	1·7	0·661	7·43	1·030	1·010	0·868	0·142
(S)	6·333	1·8	0·700	7·87	1·054	1·031	0·859	0·172
$\frac{B}{T}$	2·837	1·9	0·739	8·30	1·095	1·067	0·851	0·216
$\frac{L_{WL}}{L_{BP}}$	1·024	2·0	0·776	8·74	1·158	1·121	0·844	0·277
$\frac{\nabla^{1/3}}{L_{WL}}$ (M)	6·09 0·1642	2·1	0·817	9·18	1·264	1·220	0·837	0·383
$\frac{B}{L_{WL}}$	0·1339							
$\frac{T}{L_{WL}}$	0·0472							
$\frac{\bar{x}}{L_{WL}}$	0·4871							
$\frac{\ell}{L_{WL}}$	0·0135							
$\frac{L_{0.5T}}{L_{WL}}$	0·948							
tan α_1	0·413							
" α_2	0·412							
" α_3	0·386							
" α_4	0·385							
" α_5	0·483							
" α_6	0·583							
" α_7	0·343							
" α_8	0·343							
" α_9	0·320							
" α_{10}	0·297							
" α_{11}	0·305							
" α_{12}	0·271							

CALCULATION OF x, y AND p ASSUMING $_{o}C_{v} = x(\log R_n - 2)^{-2}$ AND $_{o}C_{w} = {}_{o}C - {}_{o}C_{v} = y K^{p}$. RESULT x 20.6 y 0.0166 p 4.00

LOG K		0.146	0.176	0.204	0.230	0.255	0.279	0.301	0.322
	$_{o}C$	0.962	0.970	0.990	1.010	1.031	1.067	1.121	1.220
	$10^{-6} R_n$	6.12	6.56	6.99	7.43	7.87	8.30	8.74	9.18
$100(\log R_n - 2)^{-2}$		4.363	4.309	4.260	4.214	4.171	4.132	4.094	4.060
x									
21.4	$_{o}C_{v}$	0.934	0.922	0.912	0.902	0.893	0.884	0.876	0.869
	$_{o}C_{w}$	0.028	0.048	0.078	0.108	0.138	0.183	0.245	0.351
	LOG $_{o}C_{w}$	$\bar{2}.447$	.681	.892	$\bar{1}.033$	.140	.262	.389	.545
21.0	$_{o}C_{v}$	0.917	0.905	0.895	0.885	0.876	0.868	0.860	0.853
	$_{o}C_{w}$	0.045	0.065	0.095	0.125	0.155	0.199	0.261	0.367
	LOG $_{o}C_{w}$	$\bar{2}.653$	.813	.978	$\bar{1}.097$	.190	.299	.417	.565
20.8	$_{o}C_{v}$	0.908	0.896	0.886	0.877	0.868	0.860	0.852	0.845
	$_{o}C_{w}$	0.054	0.074	0.104	0.133	0.163	0.207	0.269	0.375
	LOG $_{o}C_{w}$	$\bar{2}.732$	.869	$\bar{1}.017$	.124	.212	.316	.430	.574
20.0	$_{o}C_{v}$	0.873	0.862	0.852	0.843	0.834	0.826	0.819	0.812
	$_{o}C_{w}$	0.089	0.108	0.138	0.167	0.197	0.241	0.302	0.408
	LOG $_{o}C_{w}$	$\bar{2}.949$	$\bar{1}.033$	.140	.223	.294	.382	.480	.611
20.4	$_{o}C_{v}$	0.890	0.879	0.869	0.860	0.851	0.843	0.835	0.828
	$_{o}C_{w}$	0.072	0.091	0.121	0.150	0.180	0.224	0.286	0.392
	LOG $_{o}C_{w}$	$\bar{2}.857$	.959	$\bar{1}.083$	.176	.255	.350	.456	.593
20.6	$_{o}C_{v}$	0.899	0.888	0.878	0.868	0.859	0.851	0.844	0.837
	$_{o}C_{w}$	0.063	0.082	0.112	0.142	0.172	0.216	0.277	0.383
	LOG $_{o}C_{w}$	$\bar{2}.799$	.914	$\bar{1}.049$	.152	.235	.334	.442	.583

Table 2

Values of blockage coefficient k

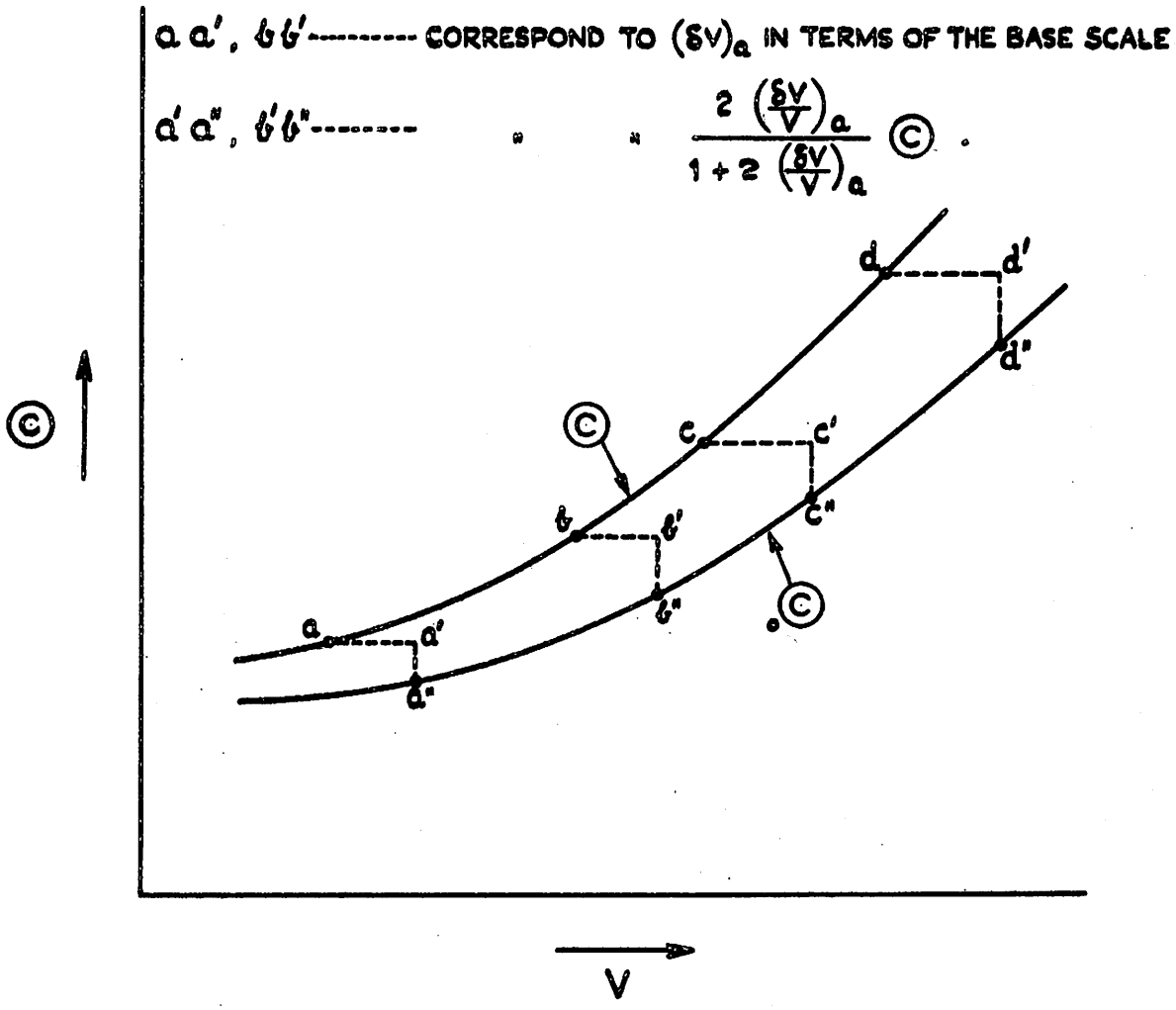
$\frac{V}{\sqrt{L_{BP}}}$	k	$\frac{V}{\sqrt{L_{BP}}}$	k
0.30	2.52	0.76	1.70
0.32	2.45	0.78	1.69
0.34	2.39	0.80	1.69
0.36	2.33	0.82	1.69
0.38	2.27	0.84	1.69
0.40	2.22	0.86	1.69
0.42	2.17	0.88	1.70
0.44	2.12	0.90	1.71
0.46	2.07	0.92	1.72
0.48	2.03	0.94	1.73
0.50	1.99	0.96	1.75
0.52	1.95	0.98	1.77
0.54	1.92	1.00	1.80
0.56	1.89	1.02	1.83
0.58	1.86	1.04	1.87
0.60	1.83	1.06	1.91
0.62	1.80	1.08	1.95
0.64	1.78	1.10	2.00
0.66	1.76	1.12	2.05
0.68	1.74	1.14	2.10
0.70	1.73	1.16	2.15
0.72	1.72	1.18	2.20
0.74	1.71	1.20	2.24

$\frac{V}{\sqrt{L_{BP}}}$ in Knots . $ft^{-\frac{1}{2}}$

VALUES OF $F = 100\ (\log R_n - 2)^{-2}$ — TABLE 3

$10^{-6}R_n$	F	$10^{-6}R_n$	F	$10^{-6}R_n$	F	$10^{-6}R_n$	F	$10^{-6}R_n$	F	$10^{-6}R_n$	F
1·00	6·250	3·0	4·989	6·0	4·379	9·0	4·073	14·0	3·775	20·0	3·558
·05	6·184 66	·1	4·957 32	·1	4·366 13	·1	4·066 7	·2	3·766 9	21·0	3·529 29
·10	6·123 61	·2	4·927 30	·2	4·353 13	·2	4·058 8	·4	3·757 9	22·0	3·503 26
·15	6·065 58	·3	4·898 29	·3	4·341 12	·3	4·050 8	·6	3·748 9	23·0	3·478 25
·20	6·010 55	·4	4·870 28	·4	4·328 13	·4	4·042 8	·8	3·740 8	24·0	3·454 24
·25	5·958 52	·5	4·843 27	·5	4·316 12	·5	4·035 7	15·0	3·731 9	25·0	3·431 23
·30	5·909 49	·6	4·816 27	·6	4·304 12	·6	4·027 8	·2	3·723 8	26·0	3·410 21
·35	5·862 47	·7	4·792 24	·7	4·292 12	·7	4·020 7	·4	3·715 8	27·0	3·389 21
·40	5·817 45	·8	4·767 25	·8	4·281 11	·8	4·013 7	·6	3·707 8	28·0	3·369 20
·45	5·775 42	·9	4·743 24	·9	4·270 11	·9	4·006 7	·8	3·699 8	29·0	3·350 19
·50	5·734 41	4·0	4·721 22	7·0	4·259 11	10·0	4·000 6	16·0	3·691 8	30·0	3·332 18
·55	5·695 39	·1	4·699 22	·1	4·248 11	·2	3·986 14	·2	3·684 7	31·0	3·315 17
·60	5·658 37	·2	4·678 21	·2	4·237 11	·4	3·973 13	·4	3·676 8	32·0	3·299 16
·65	5·622 36	·3	4·658 20	·3	4·227 10	·6	3·959 14	·6	3·669 7	33·0	3·283 16
·70	5·588 34	·4	4·638 20	·4	4·217 10	·8	3·946 13	·8	3·662 7	34·0	3·268 15
·75	5·555 33	·5	4·618 20	·5	4·207 10	11·0	3·934 12	17·0	3·654 8	35·0	3·253 15
·80	5·523 32	·6	4·599 19	·6	4·197 10	·2	3·921 13	·2	3·647 7	36·0	3·238 14
·85	5·492 31	·7	4·580 19	·7	4·187 10	·4	3·909 12	·4	3·640 7	37·0	3·224 13
·90	5·462 30	·8	4·562 18	·8	4·177 10	·6	3·898 11	·6	3·633 7	38·0	3·211 13
·95	5·434 28	·9	4·545 17	·9	4·168 9	·8	3·886 12	·8	3·626 6	39·0	3·198 13
2·00	5·406 28	5·0	4·529 16	8·0	4·159 9	12·0	3·875 11	18·0	3·620 7	40·0	3·185 12
·10	5·353 53	·1	4·512 17	·1	4·150 9	·2	3·864 11	·2	3·613 6	41·0	3·173 12
·20	5·303 50	·2	4·496 16	·2	4·141 9	·4	3·854 10	·4	3·607 7	42·0	3·161 11
·30	5·256 47	·3	4·480 16	·3	4·132 9	·6	3·843 11	·6	3·600 6	43·0	3·150 11
·40	5·212 44	·4	4·464 16	·4	4·123 9	·8	3·833 10	·8	3·594 6	44·0	3·139 11
·50	5·170 42	·5	4·449 15	·5	4·114 9	13·0	3·823 10	19·0	3·588 6	45·0	3·128 11
·60	5·130 40	·6	4·435 14	·6	4·106 8	·2	3·813 10	·2	3·582 6	46·0	3·117 10
·70	5·092 38	·7	4·420 15	·7	4·098 8	·4	3·803 10	·4	3·575 7	47·0	3·107 10
·80	5·056 36	·8	4·406 14	·8	4·089 9	·6	3·794 9	·6	3·569 6	48·0	3·097 10
·90	5·022 34	·9	4·392 14	·9	4·081 8	·8	3·784 10	·8	3·563 6	49·0	3·087 10
3·00	4·989 33	6·0	4·379 13	9·0	4·073 8	14·0	3·775 9	20·0	3·558 5	50·0	3·078 9

FIG. 1.


a a', b b'--------- CORRESPOND TO $(\delta V)_a$ IN TERMS OF THE BASE SCALE
a' a'', b' b''--------- " " $\frac{2\left(\frac{\delta V}{V}\right)_a}{1+2\left(\frac{\delta V}{V}\right)_a}$ ©.
©
V
a
a'
a''
b
b'
b''
c
c'
c''
d
d'
d''
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©

FIG. 2.

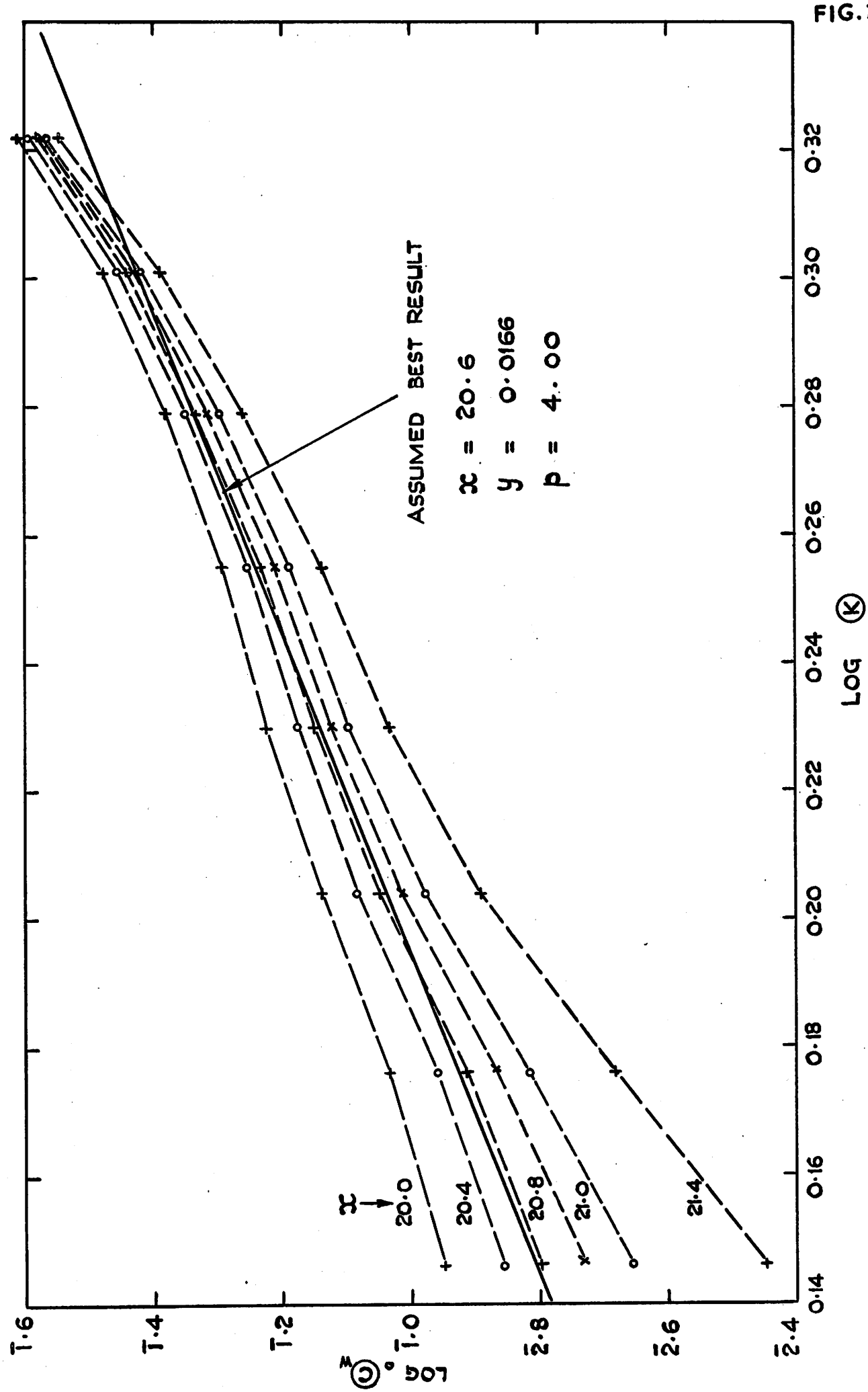
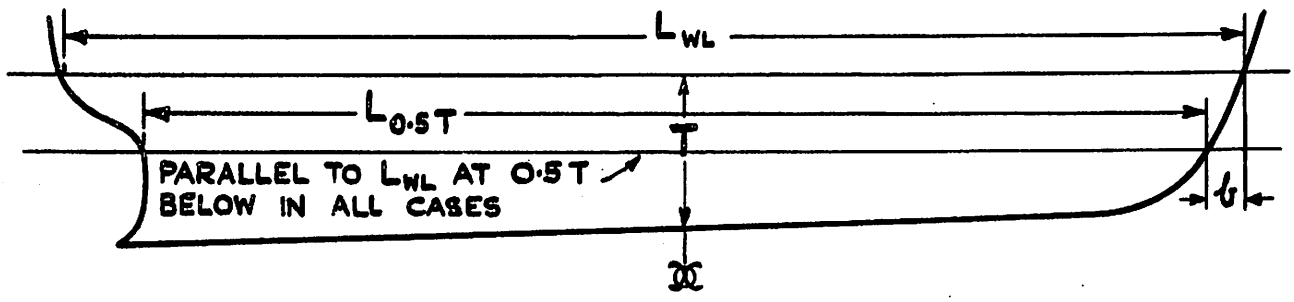
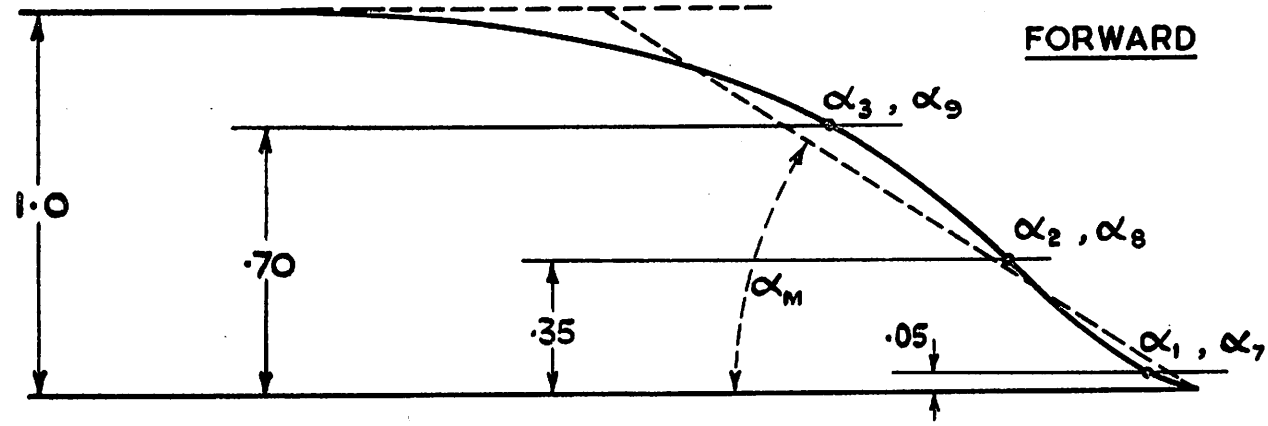
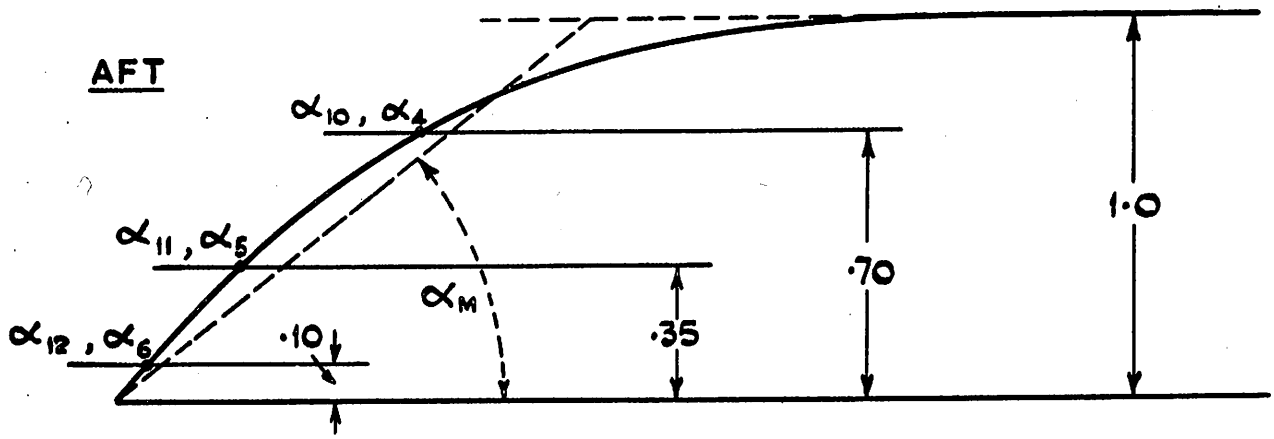
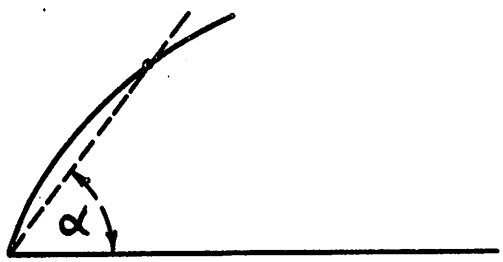

ASSUMED BEST RESULT
x = 20·6
y = 0·0166
p = 4·00
x
20·0
20·4
20·8
21·0
21·4
LOG (K)
0·14
0·16
0·18
0·20
0·22
0·24
0·26
0·28
0·30
0·32
LOG °(C)w
1·6
1·4
1·2
1·0
2·8
2·6
2·4

FIG. 3.

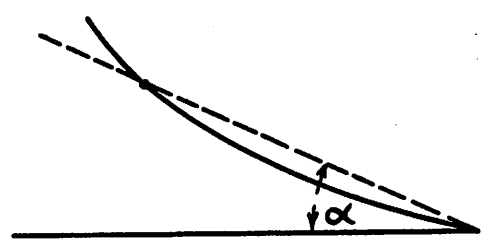








TYPICAL ANGLE α AFT.



TYPICAL ANGLE α FORWARD

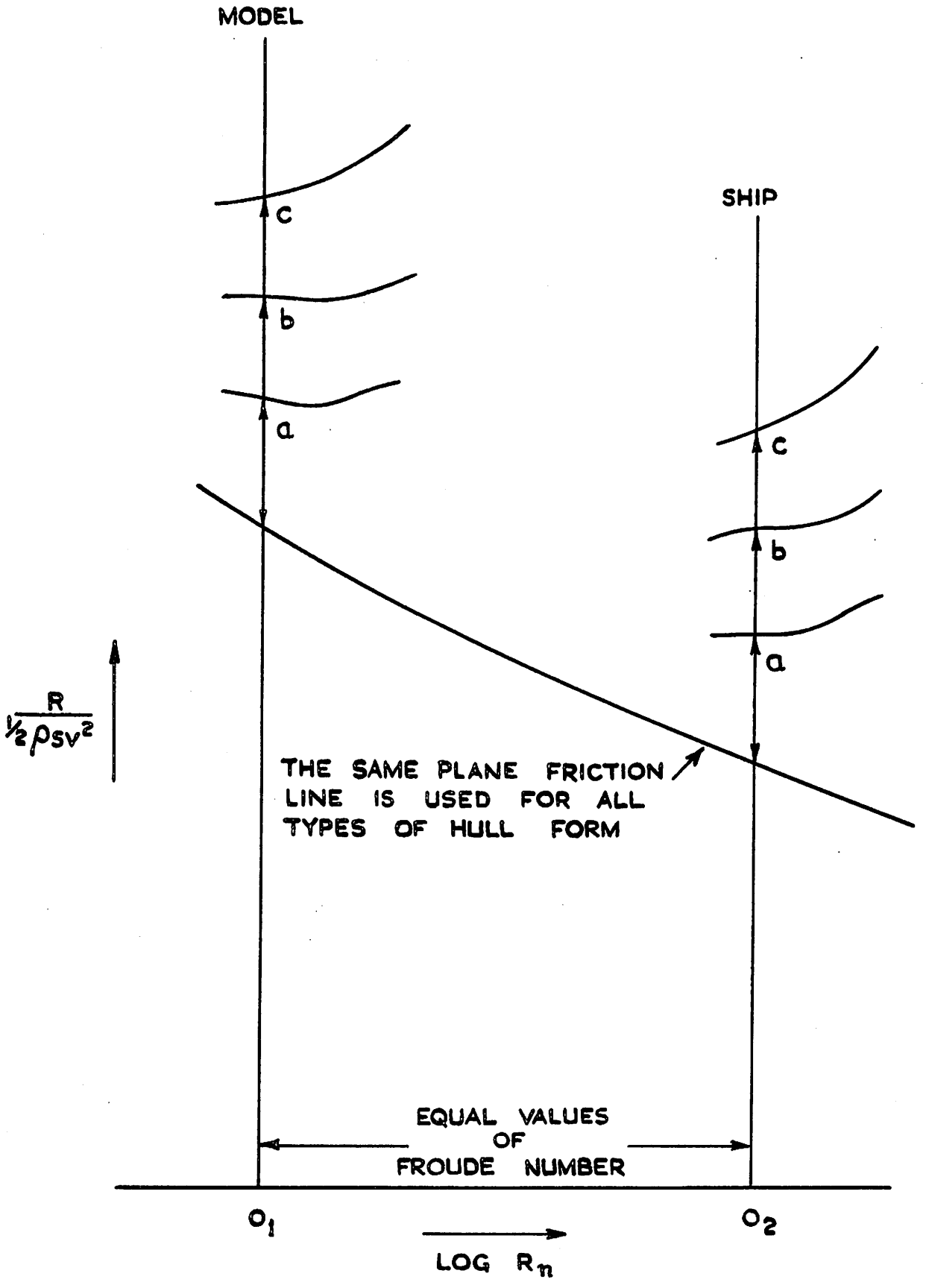
α DENOTES THE ANGLE BETWEEN THE CENTRE-LINE AND THE LINE JOINING THE END OF THE LEVEL-LINE TO ANY POINT ON THE LEVEL-LINE. THE HALF-BREADTH POSITIONS FOR THE CHOSEN POINTS ARE SHOWN ABOVE. NOTE THAT THE HALF-BREADTHS FOR α_1 , α_7 FORWARD AND FOR α_6 , α_{12} AFT ARE DIFFERENT.

α_1 TO α_6 REFER TO THE WATER-LINE AT WHICH THE MODEL FLOATS AT REST.

α_7 TO α_{12} REFER TO THE LEVEL-LINE AT 0·5 T BELOW THE WATER-LINE.

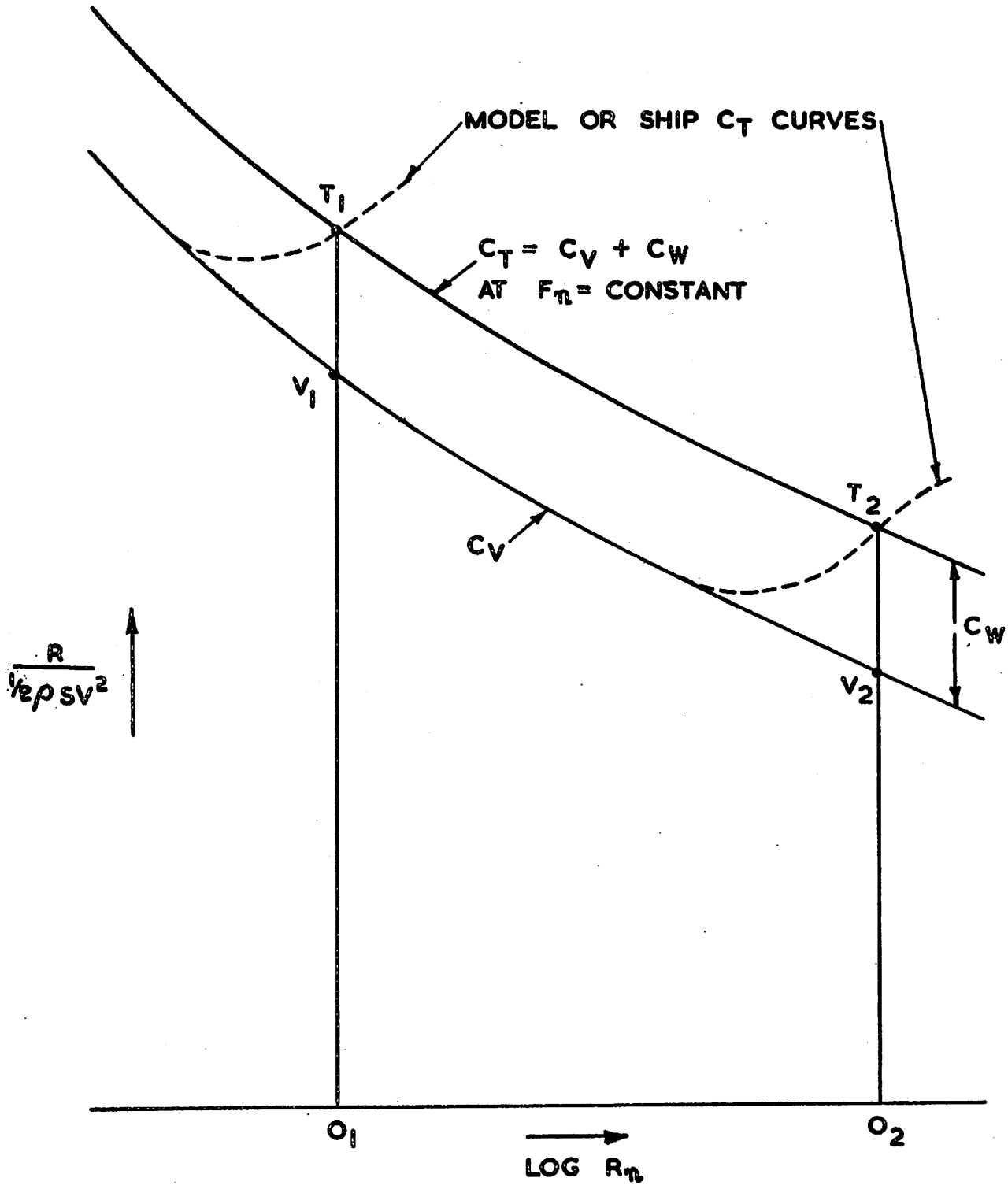
α_M DENOTES IN GENERAL A MEAN ANGLE GIVING THE SAME LEVEL PLANE AREA.

FIG. A.

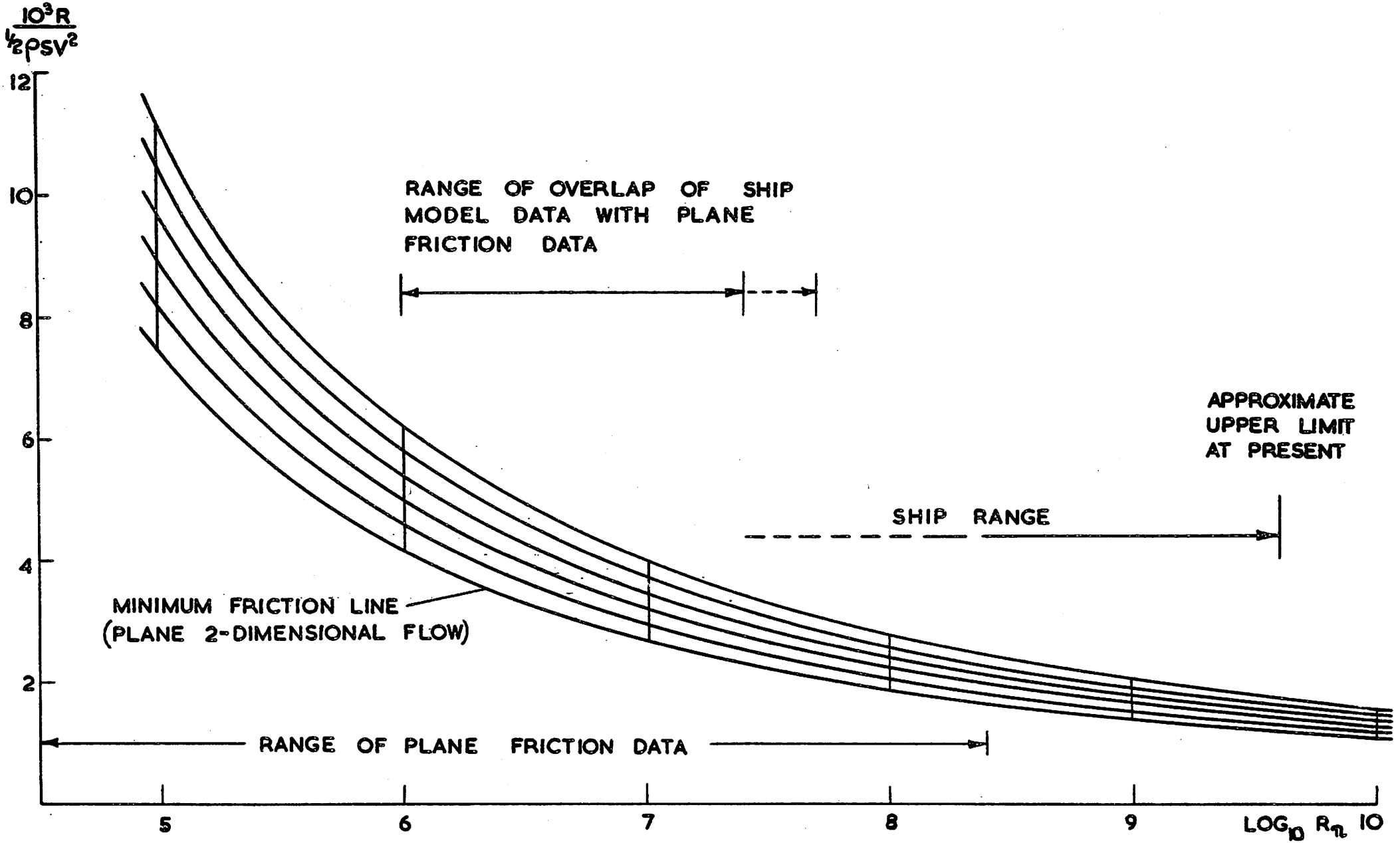


CURRENT METHOD OF APPLICATION

FIG. B.



NEW PROCEDURE



LINES OF VISCOUS RESISTANCE COEFFICIENT FOR PLANE RECTANGULAR SURFACES AND FOR SHIP MODELS

FIG. C.